

TEMPORAL CONTEXT IN CONCURRENT CHAINS: I. TERMINAL-LINK DURATION

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Two experiments are reported in which the ratio of the average times spent in the terminal and initial links (Tt/Ti) in concurrent chains was varied. In Experiment 1, pigeons responded in a three-component procedure in which terminal-link variable-interval schedules were in constant ratio, but their average duration increased across components by a factor of two. The log initial-link response ratio was a negatively accelerated function of Tt/Ti . Overall, the data were well described by Grace's (1994) contextual choice model (CCM) with temporal context represented as $(Tt/Ti)^k$ or $2Tt/(Tt + Ti)$, and by Mazur's (2001) hyperbolic value-added model (HVA), with each model accounting for approximately 93% of the variance. In Experiment 2, fixed-parameter predictions for each model were generated, based on the data from Experiment 1, for conditions in which Tt/Ti was varied over a more extreme range. Data were consistent with the predictions of CCM with temporal context represented as $2Tt/(Tt + Ti)$ and to a lesser extent as $(Tt/Ti)^k$, but not with HVA. Overall, these results suggest that preference increases as a hyperbolic function of Tt/Ti when terminal-link duration is increased relative to initial-link duration, with the terminal-link schedule ratio held constant.

Key words: choice, concurrent chains, terminal-link duration, reinforcement context, contextual choice model, hyperbolic value added model, key peck, pigeons

In the concurrent-chains procedure, subjects respond during a choice phase ("initial links") to produce access to one of two mutually exclusive outcome schedules ("terminal links"). Typically after food reinforcement has been delivered in a terminal link, the initial links are reinstated. The most common result is that subjects respond at a higher rate for the initial link that leads to the richer terminal-link schedule. For example, if the terminal links associated with the left and right initial links are fixed interval (FI) 10-s and FI 20-s schedules, respectively, then the majority of responses during the choice phase would be made to the left initial link (e.g., 75% of all initial-link responses). Because the terminal links are usually signaled by distinctive stimuli, preference in the initial links has been interpreted as a measure of the relative effectiveness or value of the terminal-link stimuli as conditioned reinforcers.

Despite the apparent simplicity of this finding, research has shown that the strength of preference for the richer terminal link depends on many factors, including the duration of the initial links (Fantino, 1969), the stimuli correlated with the terminal links (Williams & Fantino, 1978), response contingencies during the terminal links (Moore &

Fantino, 1975; Nevin, Grace, Holland, & McLean, 2001), and whether the terminal-link reinforcement delays are fixed or variable (Killeen, 1968). One focus of recent research has been the development of comprehensive models for concurrent-chains performance that are able to explain these and other results.

For example, Grace (1994) proposed an extension of the generalized matching law (Baum, 1974; Davison, 1983) as a model for concurrent chains:

$$\frac{B_L}{B_R} = b \left(\frac{R_L}{R_R} \right)^{a_1} \left[\left(\frac{1/D_L}{1/D_R} \right)^{a_2} \right]^{(Tt/Ti)^k}, \quad (1)$$

where B_L and B_R are the initial-link response rates, R_L and R_R are rates of terminal-link entry, D_L and D_R are the average delays to reinforcement from onset of the terminal links, and Tt and Ti are the average times spent in the terminal and initial links per reinforcement. There are four parameters: bias, b , sensitivity to initial-link conditioned reinforcement (a_1) and terminal-link immediacy ratios (a_2), and a context scaling parameter, k . Equation 1 is called the contextual choice model (CCM) because it specifies how temporal context, Tt/Ti , affects sensitivity to terminal-link variables: When terminal-link duration increases relative to initial-link duration, effective sensitivity to delay, $a_2(Tt/Ti)^k$, increases; when terminal-link duration

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decreases relative to initial-link duration, effective sensitivity to delay decreases. Grace (1994) showed that Equation 1 gave a better quantitative description of the data than did several models of concurrent-chains performance reviewed by Davison (1987)—delay-reduction theory (Squires & Fantino, 1971), incentive theory (Killeen, 1982), and the Davison–Temple (1973) model—accounting for over 90% of the variance in relative initial-link responding averaged over 19 studies.

Grace (1994) used the following procedure for fitting the context scaling parameter, k . Each of the 92 concurrent-chains data sets was first analyzed with k set equal to 1. If the fit of Equation 1 satisfied the criteria used by Davison (1987) to judge the adequacy of a model's fit to a data set, no further analysis was performed.¹ However, if the fit did not satisfy these criteria, k was allowed to vary. If the best-fitting value of k resulted in a fit that satisfied the criteria, or a significant improvement in variance accounted for, then the new value of k was used; otherwise k was set equal to 1. In this way, nine data sets required estimated values for k , and all of these values were less than 1. Eight of these data sets were from studies in which the terminal links were uncued (i.e., were signaled by the same stimulus), which suggests that the effect of temporal context depends on the stimulus conditions in the terminal links. For reasons of parsimony, Grace therefore suggested that k could be set equal to 1 and not treated as a free parameter for studies in which terminal links were signaled by different stimuli.

Equation 1 was proposed on the basis of a reanalysis of archival data, and was the simplest model, especially with $k = 1$, able to account for a high proportion of variance in these data. However, as Grace (1994) noted, other expressions for temporal context could have described the data equally well. Consider the following generalization of CCM:

$$\frac{B_L}{B_R} = b \left(\frac{R_L}{R_R} \right)^{a_1} \left[\left(\frac{1/D_L}{1/D_R} \right)^{a_2} \right]^{f(Tt/Ti)} \quad (2)$$

where the effect of temporal context on sen-

sitivity is an unspecified function, f , of Tt/Ti . Grace noted that any monotonic increasing f would yield a model that would likely describe the archival data about as well, in terms of variance accounted for, as Equation 1 does (which assumes f is a power function). Because Tt and Ti are, in effect, higher-order independent variables, they must be manipulated directly in order to assess their effect on preference.

If Tt and Ti are manipulated directly, we can limit alternatives for f by asking the following question: Is f a negatively accelerated, linear, or positively accelerated function? To answer this question requires examining the rate of change of preference with respect to Tt/Ti . Specifically, consider a case in which Ti is held constant and Tt increases, while the ratio of terminal-link delays is held constant. It is well-known that preference for the shorter terminal link will increase (MacEwen, 1972; Williams & Fantino, 1978). But does the rate of increase in preference decrease, remain constant, or increase as Tt increases? If $k = 1$ in Equation 1, f is linear and a constant rate of increase in preference is predicted. If $k < 1$, as in the studies for which terminal links were not differentially cued, a negatively accelerated f is obtained. Determining the rate of change of preference as a function of Tt will indicate whether k may be assumed to be equal to 1 when terminal links are cued.

An implication that f might be negatively accelerated comes from autoshaping data. Dinsmoor (1983) and others (e.g., Preston & Fantino, 1991) have commented that temporal context effects in concurrent chains and autoshaping appear to be qualitatively similar. In terms of the overall temporal relations between stimuli and reinforcers, autoshaping is analogous to concurrent chains because it consists of alternating periods of signaled nonreinforcement (intertrial interval [I] in autoshaping, Ti in concurrent chains) and signaled delays to reinforcement (trial duration [T] in autoshaping, Tt in concurrent chains). Gibbon, Baldock, Locurto, Gold, and Terrace (1977) found that rate of key-peck acquisition in autoshaping increased with increases in I , decreased with increases in T , and was approximately constant for constant ratios of I/T . But if translated into analogous concurrent-chains terms, this ratio in-

¹ The criteria Davison (1987) used were that slope and intercept estimates from a regression performed on the obtained versus predicted data did not deviate from 1.0 and 0.0, respectively, by less than two standard deviations, and that the standard error of prediction be 0.10 or less.

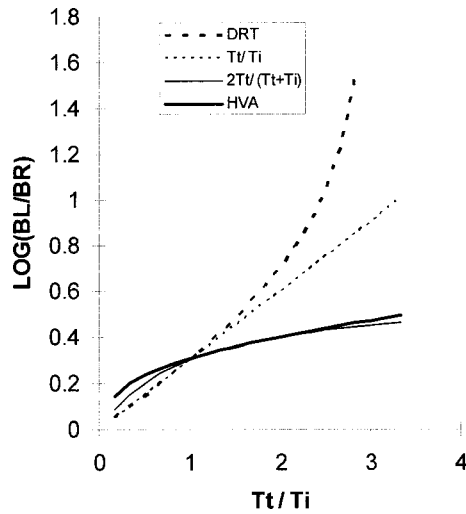


Fig. 1. The log initial-link response ratio for the shorter terminal link as a function of average terminal-link duration relative to initial-link duration (Tt/Ti), as predicted by four models: (a) delay-reduction theory (DRT), contextual choice model (CCM) with temporal context represented as (b) Tt/Ti and (c) $2Tt/(Tt+Ti)$, and (d) the hyperbolic value added (HVA) model. Predictions were made assuming a constant terminal-link ratio (2:1), equal VI 60 s initial links, and sensitivity to delay (a_2) parameters equal to 1 for both versions of CCM and HVA.

variance is the reciprocal of that predicted by CCM (i.e., terminal-link sensitivity is constant for constant ratios of Tt/Ti). Thus one possibility is that temporal context effects in the two procedures may be isomorphic.

Gibbon and Balsam (1981) presented a theoretical account of autoshaping based on Gibbon's (1977) scalar expectancy theory and building on the earlier results of Gibbon et al. (1977). They proposed that acquisition rate was a function of C/T , where C is the cycle time, or average interreinforcer interval. Their account predicts the ratio invariance reported by Gibbon et al. and explains the decrement in acquisition rate when reinforcers are delivered during I . If C/T is translated into concurrent-chains terms (and the reciprocal is taken), $Tt/(Tt + Ti)$ is obtained, which is consistent with Equation 2 for $f(x) = x/(x + 1)$. This equation predicts that preference between a pair of terminal-link schedules in constant ratio should increase towards asymptote as a negatively accelerated (hyperbolic) function of Tt . In order to retain comparability of parameter estimates when temporal context was repre-

sented as Tt/Ti , a scalar factor of 2 was included so that unit sensitivity would be obtained when $Tt = Ti$, that is, $2Tt/(Tt + Ti)$.

Another model that predicts preference should be a negatively accelerated function of Tt has recently been proposed by Mazur (2001). According to the hyperbolic value-added model (HVA), the value of each stimulus transition (i.e., onset of initial links, and each terminal link) is a function of delay to reinforcement signaled by that transition and computed according to the hyperbolic model proposed by Mazur (1984). Preference in the initial links is then determined by the relative amount of value added by the terminal-link transitions. Specifically, Mazur's model predicts that initial-link preference is given by the following equation:

$$\frac{B_L}{B_R} = b \left(\frac{R_L}{R_R} \right)^{a_i} \left(\frac{V_L - a_t V_i}{V_R - a_t V_i} \right), \quad (3)$$

in which V_L and V_R are the values of the left and right terminal links, V_i is the value of the initial links, and a_t is a sensitivity parameter. The terminal- and initial-link values are determined by applying Mazur's (1984) hyperbolic-decay function to the distributions of delays to reinforcement associated with the onset of the initial links and each of the terminal links. Note that HVA, like CCM, is based on the generalized matching law. As Mazur noted, however, the principle of "value addition"—in which a terminal link that signals a given delay to reinforcement is more effective if the initial links have a relatively low value—is essentially the same as that of delay-reduction theory (DRT; Fantino, 1969; see Fantino, Preston, & Dunn, 1993, for review). According to DRT, the value of a terminal-link stimulus is determined by the reduction in delay to reinforcement signaled by onset of the stimulus, relative to the overall average delay to reinforcement:

$$\frac{B_L}{B_R} = \frac{T - D_L}{T - D_R}, \quad (4)$$

where T is the overall average time between reinforcers. Thus a terminal link that signals a given delay to reinforcement will be a more effective conditioned reinforcer if it occurs in an overall lean reinforcement context (i.e., large value of T).

Figure 1 shows preference as a function of

Tt/Ti , scaled as the logarithm of the initial-link response ratio, predicted by several models. The models are (a) delay-reduction theory; (b) CCM with $f(x) = x(Tt/Ti)$, (c) CCM with $f(x) = 2x/(x+1)(2Tt/[Tt+Ti])$, and (d) the hyperbolic value-added model. The predictions in Figure 1 were made assuming equal variable-interval (VI) 60-s VI 60-s initial-link schedules, a constant 2:1 terminal-link delay ratio, and unit bias and sensitivity to delay values for CCM and HVA. Predictions were computed for values of Tt ranging from 5 s to 105 s.

Figure 1 shows that DRT predicts that preference will increase as a positively accelerated function, Tt/Ti requires a linear increase, and both $2Tt/(Tt+Ti)$ and HVA predict a negatively accelerated function. Thus discriminating among the models requires determining whether the rate of increase in preference increases, is constant, or decreases as Tt/Ti increases (i.e., the sign of the second derivative of preference with respect to Tt/Ti). The sign of the second derivative can be estimated empirically by obtaining preference for three pairs of terminal-link schedules in constant ratio with increasing values of Tt/Ti . Then, comparing point estimates of the first derivative gives an estimate of the sign of the second derivative. For example, if the initial links are VI 30 s VI 30 s ($Ti = 15$ s), consider the following terminal-link pairs: VI 5 s VI 10 s, VI 10 s VI 20 s, and VI 20 s VI 40 s. The ratio of terminal-link schedules is constant (2:1), and Tt increases by a factor of two (7.5 s, 15 s, 30 s) across the pairs. Thus Tt/Ti is equal to 0.5, 1, and 2. If the slope of the function relating Tt/Ti to preference is greater between $Tt/Ti = 1$ and $Tt/Ti = 2$ than the slope between $Tt/Ti = 0.5$ and $Tt/Ti = 1$, then the second derivative of preference with respect to Tt/Ti is positive, as predicted by DRT; if smaller, then negative, as predicted by $f(x) = 2x/(x+1)$, $f(x) = x^k$, $k < 1$, and HVA; if equal, then zero, as predicted by $f(x) = x$.

Two previous experiments provided some relevant data. MacEwen (1972) studied pigeons' preference between pairs of FI and VI terminal links that were always in a 2:1 ratio, and varied absolute duration across conditions. Williams and Fantino (1978) compared pigeons' preference between FI terminal links, again in constant 2:1 ratio but varying

absolute durations, that were either cued or uncued in different sets of conditions. Although both studies reported that preference was a negatively accelerated function of Tt , choice proportions were used that render it difficult to discriminate between candidates for f in Equation 2. Therefore their data were reanalyzed in log ratio form, and the results are shown in Figure 2. For all of MacEwen's subjects, preference was a negatively accelerated function of Tt ,² although nearly linear for VI terminal links for Pigeons M1 and M5. A methodological problem with MacEwen's study, however, is that the left/right position of the shorter terminal link was not varied across conditions, which fails to control for position bias. Williams and Fantino's results were more variable across subjects. In the uncued conditions, 3 out of 4 subjects showed a linear or positively accelerated relation between preference and Tt , whereas in the cued conditions the relation was linear for 2 subjects but negatively accelerated for the other 2. Overall, then, results from these studies are inconclusive as to whether preference, scaled as a log ratio, is a positively accelerated, linear, or negatively accelerated function of Tt .

Two experiments are reported here. Experiment 1 investigated how preference changes as a function of Tt/Ti when terminal-link duration is manipulated. It also provided data for which the predictions of the models discussed above could be compared. Experiment 2 used the same subjects as Experiment 1 and was conducted directly after Experiment 1 was completed. The purpose of Experiment 2 was to test fixed-parameter predictions of models fitted to data from Experiment 1 for preference over a more extreme range of Tt/Ti .

EXPERIMENT 1

Two series of conditions were conducted in Experiment 1, one in which the average programmed initial-link duration was 15 s and

² MacEwen's (1972) VI schedule values are listed as the harmonic, not arithmetic mean, and the intervals are not listed. Because Tt is calculated as the arithmetic average, an optimizing procedure was used to define, according to the Catania and Reynolds (1968) constant-probability progression that MacEwen used, schedules with the harmonic means listed. The arithmetic averages were then used for calculating Tt .

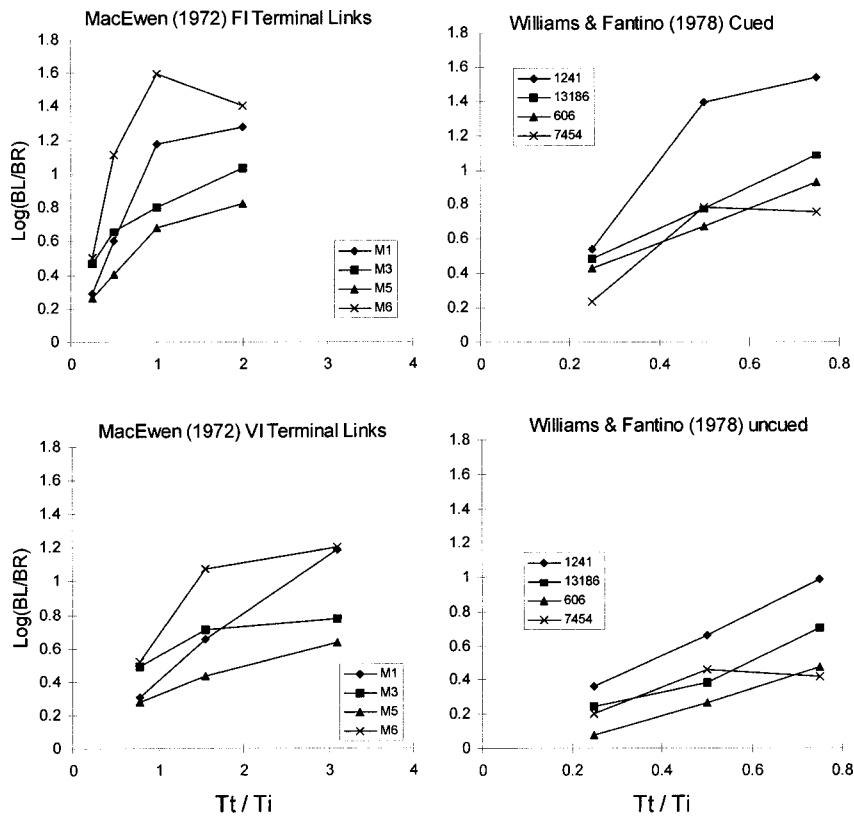


Fig. 2. Results from MacEwen (1972) and Williams and Fantino (1978), which are the only previous studies that examined preference between terminal links in constant ratio for at least three values of Tt/Ti . Preference between FI terminal links in MacEwen (1972) are negatively accelerated for all subjects (upper left panel), but the other data are mixed.

one in which it was 30 s. A multiple-component procedure was used in which subjects were exposed to three separate concurrent chains in each session (Grace, 1995). The initial links were concurrent and independent VI schedules, with no changeover delay (COD). The terminal links were VI schedules and were arranged in ratios of 2:1, 1:2, 4:1, and 1:4 across conditions. Components differed in terms of the color used for all stimuli (red, green, or white keylights), and the overall duration of the terminal links. Across components, the programmed Tt/Ti ratios were always 0.5 (red), 1 (green), and 2 (white). For example, in the $Ti = 15$ s, 2:1 condition, the terminal links were VI 5 s VI 10 s in the red component ($Tt = 7.5$ s), VI 10 s VI 20 s in the green component ($Tt = 15$ s), and VI 20 s VI 40 s in the white component ($Tt = 30$ s). In the $Ti = 15$ s, 4:1 condition, the terminal links were VI 3 s VI 12 s (red; $Tt =$

7.5 s), VI 6 s VI 24 s (green; $Tt = 15$ s), and VI 12 s VI 48 s (white; $Tt = 30$ s).

Terminal-link schedules for the $Ti = 30$ -s conditions were derived by multiplying those from the $Ti = 15$ -s conditions by 2. Thus Experiment 1 also tested the ratio invariance predicted by CCM: Preference should not change if Tt and Ti are multiplied by the same factor (see Grace & Savastano, 2000). Regardless of the function chosen for f in Equation 2, CCM predicts that preferences should be equal for pairs of conditions with the same Tt/Ti ratio.

METHOD

Subjects

Four White Carneau pigeons served as subjects, numbered 955, 956, 958, and 961. All had previous experience in a variety of experimental procedures including concurrent

chains, and were maintained at 85% of free-feeding weight ± 15 g by appropriate post-session feedings.

Apparatus

Four standard three-key operant-conditioning chambers (350 mm deep by 350 mm wide by 350 mm high) were used. The keys were 260 mm above the floor and could be trans-illuminated red, green, or white. Each chamber was equipped with a houselight located 70 mm above the center key and a grain magazine with an aperture (60 mm by 50 mm) 130 mm below the center key. The magazine was illuminated when wheat was made available. A force of approximately 0.10 N was required to operate a key, which resulted in an audible feedback click. Each chamber was enclosed in a sound-attenuating box and fitted with a ventilation fan for masking extraneous noises. Event scheduling and data recording were controlled with a MEDSTATETM Notation program and a MED-PC[®] system interfaced to an IBM[®]-compatible microcomputer.

Procedure

Because all pigeons had prior experience, training began immediately on a three-component concurrent-chains procedure. Sessions consisted of three components, each of which was a concurrent chain. Components finished after 24 initial and terminal-link cycles, each terminating in reinforcement, and were defined by the color (red, green, white) used for all stimuli in that component. A 3-min blackout separated each pair of components. The order of components within the session varied randomly from day to day. Sessions were conducted 7 days a week at approximately the same time each day.

At the start of a cycle, the side keys were illuminated the same color (red, green, or white) signifying the initial links. The initial-link schedules did not begin timing until the first response had been made to either key. This allowed postreinforcement pauses to be recorded separately and not be counted towards completion of initial-link requirements. All initial-link schedules contained 12 intervals constructed from an arithmetic progression, $a, a + d, a + 2d, \dots$, in which a equals one-twelfth, and d equals one-sixth, the schedule value. Intervals were sampled without replacement. Arithmetic progressions

were used for the initial-link schedules to limit the variability in obtained time spent in the initial links compared with exponential progressions.

The initial links were independent concurrent VI VI schedules: a single VI schedule with an average interreinforcer interval equal to $2 \cdot T_i$ for that condition was associated with each key. When an interval from either schedule timed out, the next response to that key (as long as it was not the first response to either key following a reinforcer) produced a terminal-link entry, and timing for that initial link was stopped until the entry had been obtained. During the terminal links, timing for both initial-link schedules was stopped.

Terminal-link entry was signaled by a change from continuous to blinking illumination on the keylight, coupled with the other keylight being darkened. Keylights blinked at the rate of twice per second during the terminal links (0.25-s off, 0.25-s on). Responding during the terminal links was reinforced according to VI schedules containing 12 intervals derived from the exponential progression given by Fleshler and Hoffman (1962). Intervals from the terminal-link VI schedules were sampled randomly without replacement. When a terminal-link response was reinforced, the keylights and houselight were extinguished and the grain magazine raised and illuminated for 2.5 s. After reinforcement, the keylights and houselight were reilluminated and the next cycle began, unless the 24th reinforcer in the component had occurred, in which case the 3-min inter-component blackout began (or, if following the third component, the end of the session).

Experimental conditions were defined by the programmed average time in the initial links (T_i) and the terminal-link schedules in the green component. In all conditions, the programmed average time in the terminal links (T_t) in the green component was equal to programmed T_i . Terminal-link schedules for the red and white components were obtained by multiplying the intervals from the green component schedules by 0.5 and 2, respectively. Thus, for each condition, across the components the ratio between the terminal links was constant but programmed T_t/T_i was equal to 0.5, 1, or 2. Specifically, terminal-link schedules were as follows. For $T_i = 15$, 2:1 terminal-link ratio: VI 5 s VI 10

Table 1

Order of conditions for all subjects in Experiment 1. Each condition was uniquely defined by a combination of programmed Ti and terminal-link schedule ratio (TL ratio).

Pigeon							
955		956		958		961	
TL ratio	Ti	TL ratio	Ti	TL ratio	Ti	TL ratio	Ti
4:1	15	2:1	30	2:1	15	4:1	30
1:4	15	1:2	30	1:2	15	1:4	30
2:1	15	4:1	30	4:1	15	2:1	30
1:2	15	1:4	30	1:4	15	1:2	30
4:1	30	2:1	15	2:1	30	4:1	15
1:4	30	1:2	15	1:2	30	1:4	15
2:1	30	4:1	15	4:1	30	2:1	15
1:2	30	1:4	15	1:4	30	1:2	15

s (red), VI 10 s VI 20 s (green), VI 20 s VI 40 s (white). For $Ti = 15$, 4:1 terminal-link ratio: VI 3 s VI 12 s (red), VI 6 s VI 24 s (green), VI 12 s VI 48 s (white). For $Ti = 30$, 2:1 terminal-link ratio: VI 10 s VI 20 s (red), VI 20 s VI 40 s (green), VI 40 s VI 80 s (white). For $Ti = 30$, 4:1 terminal-link ratio: VI 6 s VI 24 s (red), VI 12 s VI 48 s (green), VI 24 s VI 96 s (white).

Table 1 lists the sequence of conditions for all subjects. Order of conditions was counter-balanced. To control for position bias, a successive-reversal design was used in which conditions were arranged in pairs that had the same terminal-link schedules, differing only in the position of the richer terminal link. For the first condition in each pair, the richer terminal link was on the left; for the second, on the right. Conditions were continued for a minimum of 25 and a maximum of 35 sessions, but were terminated prior to maximum for a particular subject if both a formal and an informal stability criterion had been satisfied for all components. The formal criterion was that the median log initial-link response rate ratio for the preceding five sessions did not differ by more than 0.1 from the median of the five immediately preceding sessions. This criterion had to be satisfied five times, not necessarily consecutively. The informal criterion was that visual inspection did not find a systematic trend over the last 10 sessions in any component. The maximum exposure of a condition was limited to 35 sessions because, in the author's experience with this procedure, stability is generally achieved by that time and extended training

may interfere with subsequent terminal-link reversals.

RESULTS

Data were aggregated across the last 10 sessions of each condition. Obtained initial-link responses and terminal-link entries are listed for all subjects and conditions in the Appendix.

Although the initial links were equal concurrent VI VI schedules in all conditions, they were independent and thus the obtained numbers of terminal-link entries could differ. Because unequal terminal-link entry frequency affects preference according to the models of Grace (1994) and Mazur (2001), the following procedure was used to compensate for the effect of unequal entries. Because both CCM (Equation 1) and HVA (Equation 3) assume that relative terminal-link entry frequency combines additively (in logarithmic terms) with the effects of bias and terminal-link delay, the obtained log relative terminal-link entry ratio was subtracted from the log relative initial-link response ratio for all conditions prior to analysis. In effect, this fixes the sensitivity parameter for unequal terminal-link entries equal to 1 (see Grace, 1999).

The logarithm of the initial-link response ratio in each condition as a function of the programmed Tt/Ti value is displayed in Figures 3 and 4 for all subjects. Figure 3 shows data from conditions in which the terminal link associated with the shorter VI schedule was on the left; Figure 4 presents data from conditions in which the shorter terminal link was on the right. In all cases, log initial-link

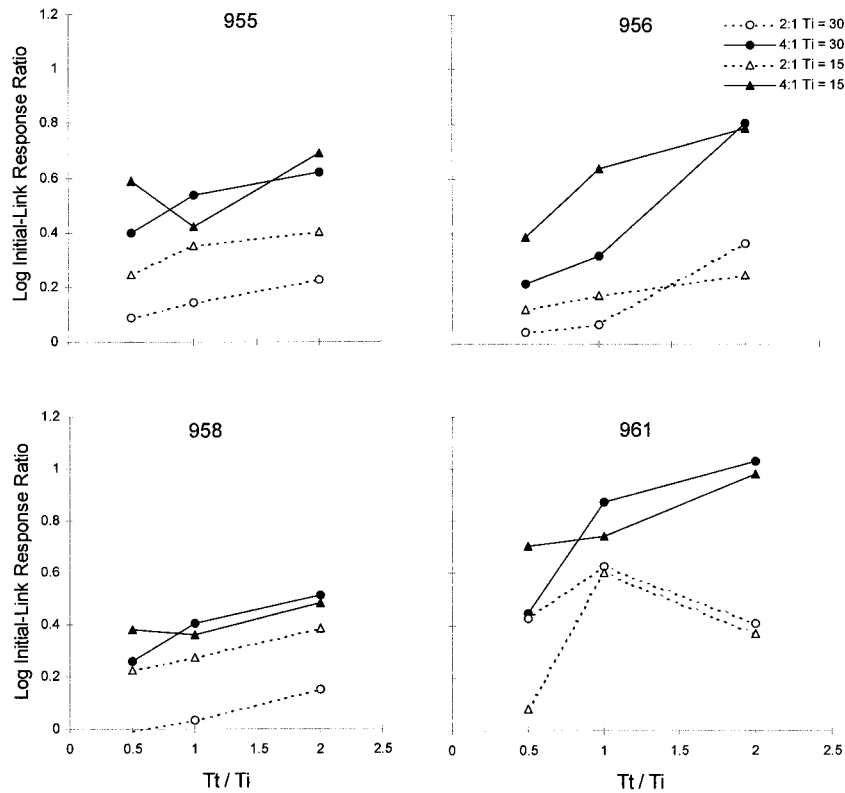


Fig. 3. The log initial-link response ratio for the left terminal link in Experiment 1, as a function of programmed Tt/Ti , for the conditions in which the shorter terminal link was on the left key. Data for conditions in which programmed Ti was equal to 15 s are marked with triangles; data are marked with circles for programmed Ti equal to 30 s. Data for conditions with a 4:1 terminal-link delay ratio are connected with a solid line, and a dashed line for a 2:1 terminal-link delay ratio.

response ratios were corrected for unequal terminal-link entries by first subtracting the obtained log entry ratio.

It is clear from Figures 3 and 4 that overall, the strength of preference increased with increases in Tt/Ti . Log initial-link response ratios increased as a function of Tt/Ti in Figure 3 when the richer terminal link was on the left, and decreased in Figure 4 when the richer terminal link was on the right. This demonstrates the so-called "terminal-link effect," which has been obtained in prior studies (MacEwen, 1972; Williams & Fantino, 1978). It is also evident that the log initial-link response ratio covaried with the ratio of the terminal-link schedules. For all subjects, data from conditions with a 4:1 or 1:4 ratio (points connected by solid lines) are more extreme than data from conditions with a 2:1 or 1:2 ratio (points connected by dashed lines). This indicates that preference in the initial

links depends on the ratio of the terminal-link schedules, similar to many prior studies (e.g., Herrnstein, 1964).

The primary question in Experiment 1 was whether preference was a positively accelerated, linear, or negatively accelerated function of Tt/Ti . Visual inspection of Figures 3 and 4 suggests that preference may have generally changed as a negatively accelerated function of Tt/Ti , although there were exceptions (e.g., Pigeons 956 and 958 in Figure 3; Pigeon 961 in Figure 4). For a more quantitative analysis, slopes were calculated for the change in preference between $Tt/Ti = 0.5$ and $Tt/Ti = 1$, and for the change between $Tt/Ti = 1$ and $Tt/Ti = 2$. Note that these slopes correspond to point estimates of the derivative of preference with respect to Tt/Ti for 0.75 and 1.5. So that the slopes for all conditions would be comparable (i.e., higher values indicate greater change in prefer-

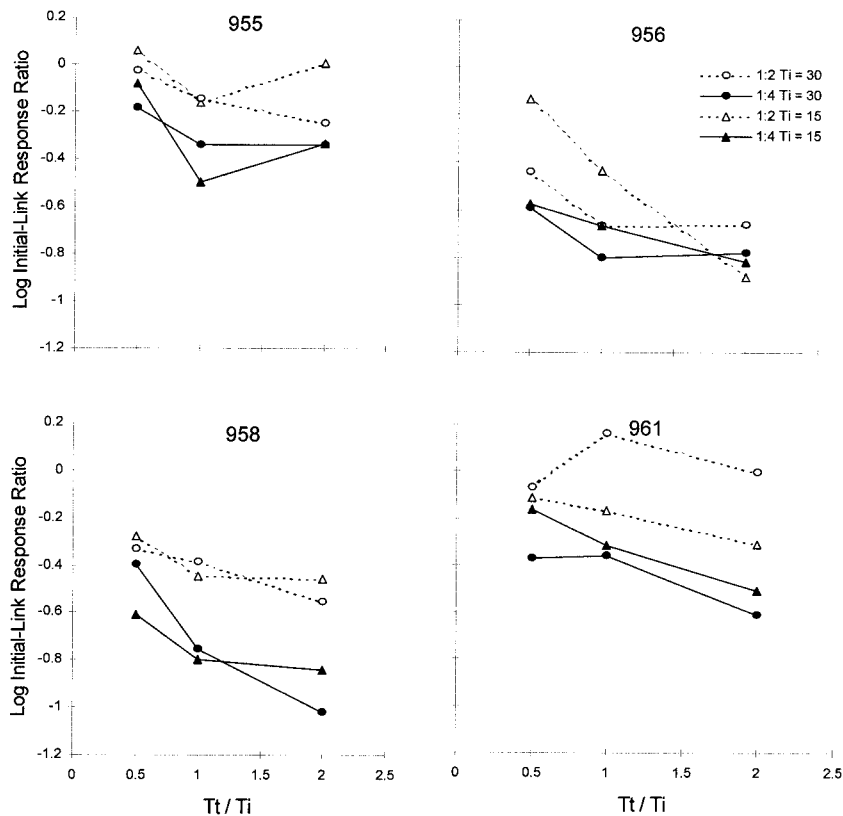


Fig. 4. The log initial-link response ratio for the left terminal link in Experiment 1, as a function of programmed Tt/Ti , for the conditions in which the shorter terminal link was on the right key. Data for conditions in which programmed Ti was equal to 15 s are marked with triangles; data are marked with circles for programmed Ti equal to 30 s. Data for conditions with a 4:1 terminal-link delay ratio are connected with a solid line, and a dashed line for a 2:1 terminal-link delay ratio.

ence), slopes for conditions in which the richer terminal link was on the right were multiplied by -1 . Data are listed in Table 2.

On average, the slope of preference as a function of Tt/Ti was greater for the change between $Tt/Ti = 0.5$ and $Tt/Ti = 1$, $M = 0.28$, than for the change between $Tt/Ti = 2$ and $Tt/Ti = 1$, $M = 0.11$. The slopes decreased in 21 out of 32 individual comparisons. Data in Table 2 were entered into a repeated-measures analysis of variance (ANOVA) with Tt/Ti , absolute value of Ti (15 s or 30 s), terminal-link ratio, and location of the richer terminal link as factors. The effect of Tt/Ti was significant, $F(1, 3) = 37.91$, $p < .01$. No other main effects or interactions were significant. This is evidence that preference is a negatively accelerated function of Tt/Ti . This result is challenging for both delay-reduction theory (Fantino et al., 1993),

which predicted a positively accelerated function, and the simplest version of CCM, in which temporal context is represented by Tt/Ti [i.e., $f(x) = x$ in Equation 2], which predicted a linear function. The negatively accelerated function is consistent with two versions of CCM, discussed above, in which context is represented as either (a) $2Tt/(Tt + Ti)$ [i.e., $f(x) = 2x/(x + 1)$], or (b) $(Tt/Ti)^k$, $k < 1$, which Grace (1994) found described data from studies in which the terminal links were uncued better than the simplest version of CCM (i.e., $k = 1$) did. The negatively accelerated function is also consistent with Mazur's (2001) HVA model. Similar results were obtained in this analysis if log initial-link response ratios uncorrected for unequal terminal-link entries were used.

A second question addressed by Experiment 1 was whether the ratio invariance pre-

Table 2

Point estimates of the slope of the relation between preference and the programmed T_l/T_i ratio for all subjects in Experiment 1. Slopes were computed for $T_l/T_i = 0.75$ by dividing the difference in preference between $T_l/T_i = 1$ and $T_l/T_i = 0.5$ by 0.5, and for $T_l/T_i = 1.5$ by taking the difference in preference between $T_l/T_i = 2$ and $T_l/T_i = 1$. The sign of slopes for conditions in which the richer terminal link was on the right was reversed. Also listed below are the average (avg.) and standard deviation (s.d.) of the slopes for each value of T_l/T_i .

	Pigeon							
	955		956		958		961	
	0.75	1.5	0.75	1.5	0.75	1.5	0.75	1.5
4:1								
($T_i=15$)	-0.33	0.27	0.50	0.15	-0.04	0.12	0.08	0.24
1:4								
($T_i=15$)	0.83	-0.16	0.19	0.15	0.38	0.04	0.30	0.20
2:1								
($T_i=15$)	0.22	0.05	0.10	0.08	0.09	0.12	1.04	-0.24
1:2								
($T_i=15$)	0.44	-0.17	0.60	0.45	0.34	0.01	0.11	0.14
4:1								
($T_i=30$)	0.28	0.08	0.20	0.48	0.29	0.11	0.86	0.15
1:4								
($T_i=30$)	0.31	0.00	0.42	-0.02	0.71	0.27	-0.02	0.25
2:1								
($T_i=30$)	0.10	0.08	0.06	0.30	0.08	0.12	0.39	-0.22
1:2								
($T_i=30$)	0.23	0.10	0.45	0.00	0.11	0.17	-0.46	0.16
	0.75	1.5						
avg.	0.28	0.11						
s.d.	0.31	0.16						

dicted by all versions of CCM and DRT characterized choice in concurrent chains (corresponding predictions of HVA are discussed below). This invariance requires that terminal-link sensitivity depends on the relative, not absolute, values of T_l and T_i ; in other words, preference should not change if T_l and T_i are multiplied by the same constant. Specifically, preference in the conditions in which the terminal-link ratio is the same but T_i varies should be equal (e.g., 2:1 $T_i = 15$ and 2:1 $T_i = 30$), because T_l/T_i is equal for corresponding components in these conditions. Graphically, this means that the pairs of both dashed and solid lines in Figures 3 through 4 should superpose.

Visual inspection of Figures 3 and 4 reveals approximate superposition, within reasonable measurement error. The mean absolute deviation between pairs of points that were predicted to have equal preference, pooled across subjects (48 pairs), was 0.13 log units. Importantly, this deviation appeared to be unsystematic. When deviations were expressed

as a signed difference, with positive numbers representing more extreme preference in the $T_i = 15$ condition, 25 deviations were positive and 23 were negative. Signed deviations were entered into a repeated-measures ANOVA with terminal-link ratio, location of the richer terminal link, and programmed T_l/T_i value as factors. There were no significant main effects or interactions. This suggests that deviations from the ratio invariance prediction were unsystematic.

A second way to assess whether deviations from ratio invariance might have been systematic is to plot preference in the $T_i = 30$ conditions as a function of preference in the corresponding $T_i = 15$ condition. Figure 5 shows the result of this analysis. The data points fall unsystematically around the major diagonal indicating equality. The best-fitting regression line accounts for 89% of the variance, with a slope and intercept close to 1.0 and 0.0, respectively. Thus deviations from equality were relatively small and unsystematic, which supports the prediction of CCM

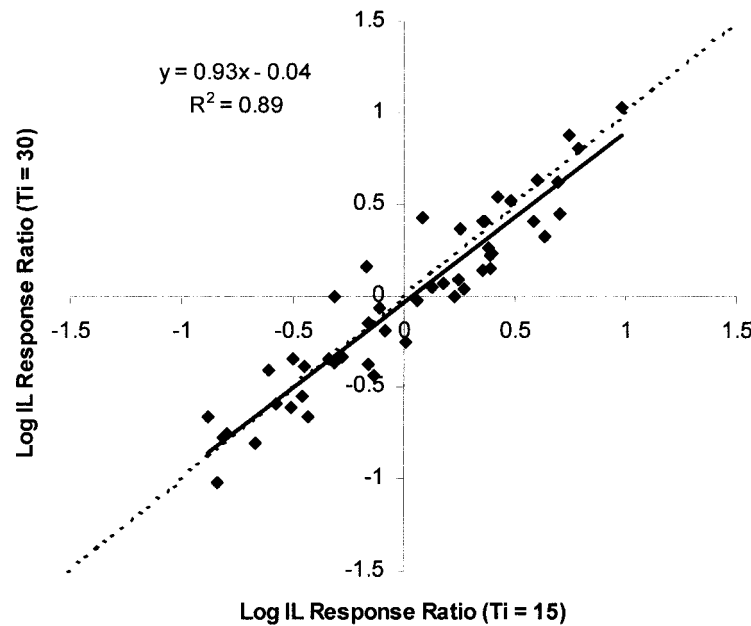


Fig. 5. Scatterplot showing the log initial-link response ratio for conditions with $T_i = 30$ as a function of the log initial-link response ratio for the corresponding condition with the same terminal-link ratio and $T_i = 15$ s. The major diagonal (light line; $y = x$) is shown, along with the best-fitting regression (heavy line). Data are pooled across subjects.

and DRT. This suggests that temporal context effects in concurrent chains are characterized by a ratio invariance property, at least for independent initial links and the particular VI schedules employed in Experiment 1.

Deviations from ratio invariance were slightly greater if uncorrected log initial-link response ratios were used. The average absolute deviation increased to 0.15 log units, but the ANOVA on the signed deviations still found no significant main effects or interactions. Thirty of the deviations were positive and 10 were negative, suggesting there was a tendency for response allocation to be more extreme in conditions with overall shorter initial- and terminal-link duration ($T_i = 15$). However, this tendency was confounded with differences in obtained terminal-link entry frequency, which according to CCM (and HVA) will produce deviations from ratio invariance.

An analysis was conducted to determine whether one of the several models discussed above provided an optimal description of the data in terms of overall variance accounted for. Four models were considered: CCM with temporal context represented as Tt/T_i , $(Tt/T_i)^k$, $2Tt/(Tt + T_i)$, and HVA. The data fitted

were the log initial-link response ratios, corrected for unequal terminal-link entries. The programmed initial- and terminal-link delay values were used. For HVA, the hyperbolic discounting parameter (K ; Mazur, 1984) was fixed at 0.2, and the distribution of times spent in the initial links was approximated by an arithmetic VI schedule with a value equal to T_i (cf. Mazur, 2001). All models were fitted to data from each subject, and estimated parameter values that maximized variance accounted for were obtained using a nonlinear optimization procedure (Microsoft® Excel Solver).

Table 3 shows that three models— $(Tt/T_i)^k$, $2Tt/(Tt + T_i)$, and HVA—provided an excellent overall description of the data, each accounting for about 93% of the variance averaged across subjects. Sensitivity to delay estimates in CCM (a_2) were close to 1.0 for 3 subjects, indicating approximate matching to relative immediacy of reinforcement. This is consistent with prior research; Grace (1994) found that sensitivity estimates for studies using VI terminal links averaged 0.90. With temporal context represented as $(Tt/T_i)^k$, estimated values of the k parameter were all less than 1, ranging between 0.35 and 0.49. When

Table 3

Estimated parameter values and variance accounted for (VAC) when four models—CCM with context represented as Tt/Ti , $(Tt/Ti)^k$, or $2Tt/(Tt+Ti)$, and HVA—were fitted to the data from all subjects in Experiment 1.

Model	Pigeon															
	955				956				958				961			
	b	a_2	k	VAC	b	a_2	k	VAC	b	a_2	k	VAC	b	a_2	k	VAC
(Tt/Ti)	1.26	0.49		0.828	0.73	0.80		0.894	0.72	0.71		0.890	1.54	0.71		0.858
$(Tt/Ti)^k$	1.26	0.66	0.35	0.912	0.73	1.01	0.49	0.942	0.72	0.93	0.39	0.963	1.54	0.93	0.41	0.919
$2Tt/(Tt+Ti)$	1.26	0.66		0.911	0.73	1.05		0.942	0.72	0.94		0.961	1.54	0.95		0.924
HVA	1.26	0.60		0.903	0.73	1.05		0.934	0.72	1.00		0.957	1.54	1.02		0.924

Average VAC: (Tt/Ti) , 0.868; $(Tt/Ti)^k$, 0.935; $2Tt/(Tt+Ti)$, 0.934; HVA, 0.929.

the k parameter was not used, the variance accounted for by CCM dropped considerably (87%). Because values of $k < 1$ predict that preference will be a negatively accelerated function of Tt/Ti , this suggests that the three models that predicted such a negatively accelerated function were able to provide comparable accounts of the data, with a substantial proportion of variance accounted for. However, it is important to recognize that CCM with temporal context represented as $(Tt/Ti)^k$ is less parsimonious than both $2Tt/(Tt+Ti)$ and HVA because it contains an additional free parameter. Unless this parameter can be justified in terms of substantially improving the overall fit, it suggests that $2Tt/(Tt+Ti)$ is a better approximation to temporal context effects in concurrent chains, at least when terminal-link duration is manipulated relative to initial-link duration.

As noted above, both CCM and DRT pre-

dicted a ratio invariance in which each preference in the $Ti = 15$ -s conditions should be equal to the corresponding $Ti = 30$ -s conditions. This prediction is necessarily implied by the way these models represent temporal context (see Grace & Savastano, 2000). By contrast, HVA does not necessarily require the ratio invariance, although depending on parameter values the approximation can be close. Thus it is important to check whether the deviations from ratio invariance predicted by HVA might be positively correlated with the obtained deviations. If so, that would imply that there was a systematic pattern of deviation from ratio invariance, and that HVA was capable of describing that pattern.

Figure 6 plots the deviation from ratio invariance predicted by HVA as a function of the obtained deviation from ratio invariance pooled across conditions and subjects. The deviation from ratio invariance was computed as the absolute value of the log initial-link response ratio in the $Ti = 15$ -s condition minus the absolute value of the log initial-link response ratio in the corresponding $Ti = 30$ -s condition (i.e., positive deviation indicates more extreme preference in $Ti = 15$ s). As Figure 6 shows, there was no positive correlation between the HVA prediction and the obtained deviation from ratio invariance. The points scatter unsystematically around the origin. Overall, the correlation was negative, $r = -0.13$, although not statistically significant. This provides further support for the conclusion that deviation from the ratio invariance prediction was unsystematic.

For a model to provide a complete description of the data, accounting for a high proportion of variance is insufficient; deviations

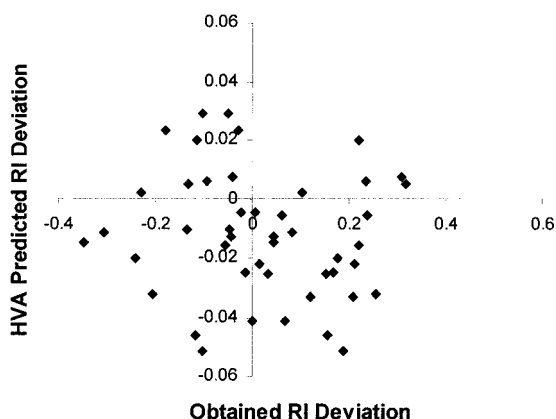


Fig. 6. Deviation from ratio invariance predicted by HVA as a function of the obtained deviation from ratio invariance. Data are pooled across subjects.

in the model's predictions (residuals) also must be unsystematic. If the model makes systematic errors in prediction, it implies that some structure in the data is not captured by the model. To examine this possibility, a series of exploratory analyses was conducted using the residuals from the three models that accounted for a high proportion of variance in the data. Residuals were computed as the obtained data minus the predicted value. The residuals from the fits of CCM with temporal context represented as $(Tt/Ti)^k$, $2Tt/(Tt + Ti)$, and HVA were all found to be approximately normally distributed (nonsignificant Kolmogorov-Smirnov tests). Scatterplots showed that for all three models there was no systematic relation between predicted and residual values, and residuals were homoscedastic (i.e., equal variance across the range of predicted values). Thus this analysis suggests that there was no systematic structure in the data that failed to be captured by the three models.

EXPERIMENT 2

The major result from Experiment 1 was that preference is a negatively accelerated function of Tt/Ti when terminal-link duration is manipulated relative to initial-link duration in concurrent chains. However, three models, CCM with temporal context represented as $(Tt/Ti)^k$ and $2Tt/(Tt + Ti)$, and Mazur's (2001) HVA model provided comparable descriptions of the data, with each accounting for about 93% of the variance. The purpose of Experiment 2 was to explore a more extreme range of variation in terminal-link duration relative to initial-link duration. Because the same subjects were used and Experiment 2 began immediately after the conclusion of Experiment 1, it provides an opportunity to test the three models in terms of fixed-parameter predictions for the new conditions. Specifically, subjects completed two conditions in which the initial links were concurrent independent VI 16-s VI 16-s schedules ($Ti = 8$ s) and the terminal-link schedule pairs were VI 16 s VI 32 s ($Tt = 24$ s), VI 32 s VI 64 s ($Tt = 48$ s), and VI 64 s VI 128 s ($Tt = 96$ s). In this way, the programmed Tt/Ti values were 3, 6, and 12, significantly extending the range from Experiment 1 in which the maximum Tt/Ti value was 2. For each

model, predictions for the new conditions were made using the best-fitting parameter estimates that had been obtained from Experiment 1. The critical question was which model, if any, would accurately predict preference over a more extended range of Tt/Ti values.

METHOD

Subjects and Apparatus

Same as in Experiment 1.

Procedure

The same three-component concurrent chains procedure as in Experiment 1 was used. Experiment 2 consisted of two conditions. In both conditions, the initial links were independent concurrent VI 6-s VI 16-s schedules, defined according to an arithmetic distribution and with no COD. For the first condition, the terminal-link schedules were as follows: VI 32 s VI 16 s (red), VI 64 s VI 32 s (green), VI 128 s VI 64 s (white). For the second condition, the terminal-link schedules were reversed within each pair. Each condition was terminated when all subjects had met the formal stability criterion used in Experiment 1, resulting in 33 sessions of training for the first condition and 40 sessions for the second condition.

RESULTS

The data were summed across the last 10 sessions of each condition, and the log initial-link response ratios were corrected by subtracting the log obtained terminal-link entry ratio. Figure 7 shows the data from Experiment 2 for all conditions and subjects. As in Experiment 1, the programmed Tt/Ti delay ratio increased by a factor of two across successive components. Unlike Experiment 1, however, there was no evidence that the strength of preference consistently increased with increases in Tt/Ti . Changes were relatively small across components. Averaged across conditions and subjects, average log response ratios were 0.42, 0.43, and 0.46 for the $Tt/Ti = 3$, 6, and 12 components, respectively. Thus increases in preference were relatively small across components, compared with Experiment 1 in which increases of more than 0.5 log units were common.

The primary purpose of Experiment 2 was to evaluate the accuracy of the fixed-param-

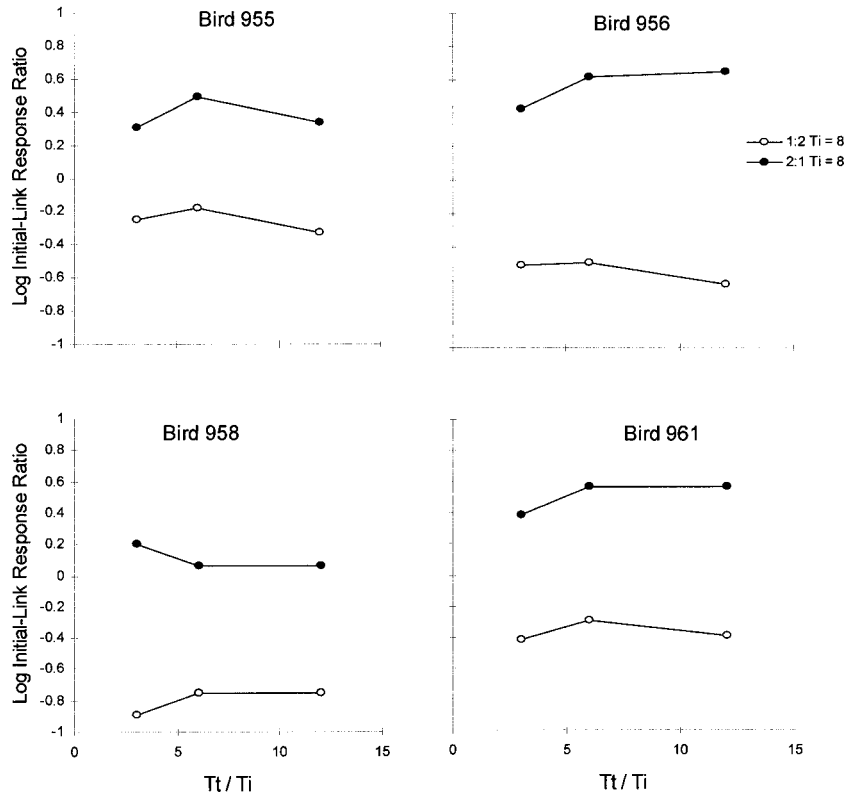


Fig. 7. The log initial-link response ratio for the left terminal link in Experiment 2 as a function of programmed Tt/Ti . Data for conditions in which the terminal-link ratio was 2:1 are marked with filled symbols; data from conditions in which the ratio was 1:2 are marked with unfilled symbols.

eter predictions made by the various models fit to the data from Experiment 1. Only models that correctly predicted that preference was a negatively accelerated function of Tt/Ti in Experiment 1 were used. Results are shown in Figure 8, which depicts the obtained log initial-link response ratios (corrected) as a function of the predictions of CCM with temporal context represented as $(Tt/Ti)^k$ and $2Tt/(Tt + Ti)$, and HVA. Figure 8 shows that there was a clear differentiation between the models in terms of prediction accuracy. Averaged across conditions and subjects, the average absolute deviation of the obtained from predicted values was 0.136 log units for $2Tt/(Tt + Ti)$, 0.196 log units for $(Tt/Ti)^k$, and 0.424 log units for HVA. CCM with temporal context represented as $2Tt/(Tt + Ti)$ made the most accurate predictions, and deviations were unsystematic. HVA made predictions that were systematically too extreme for 3 pigeons (the exception being Pi-

geon 955). Predictions of $(Tt/Ti)^k$ were intermediate in terms of accuracy.

We also conducted an analysis in which the models were fitted to the data from Experiment 2, and the resulting parameter values used to make predictions for Experiment 1. As shown in Table 4, all models accurately described the data in Experiment 2, with $(Tt/Ti)^k$, $2Tt/(Tt + Ti)$, and HVA accounting for an average of 98%, 97% and 95% of the variance, respectively. Compared with Experiment 1, parameter estimates deviated systematically for $(Tt/Ti)^k$ and HVA. For $(Tt/Ti)^k$, estimated values for a_2 and k were higher and lower, respectively, and for HVA, estimated values for a_2 were lower than Experiment 1. In contrast, estimated values of a_2 for $2Tt/(Tt + Ti)$ were close to those obtained in Experiment 1 and did not deviate systematically.

Figure 9 shows the obtained log initial-link response ratios (corrected) from Experiment 1 as a function of the models' predictions us-

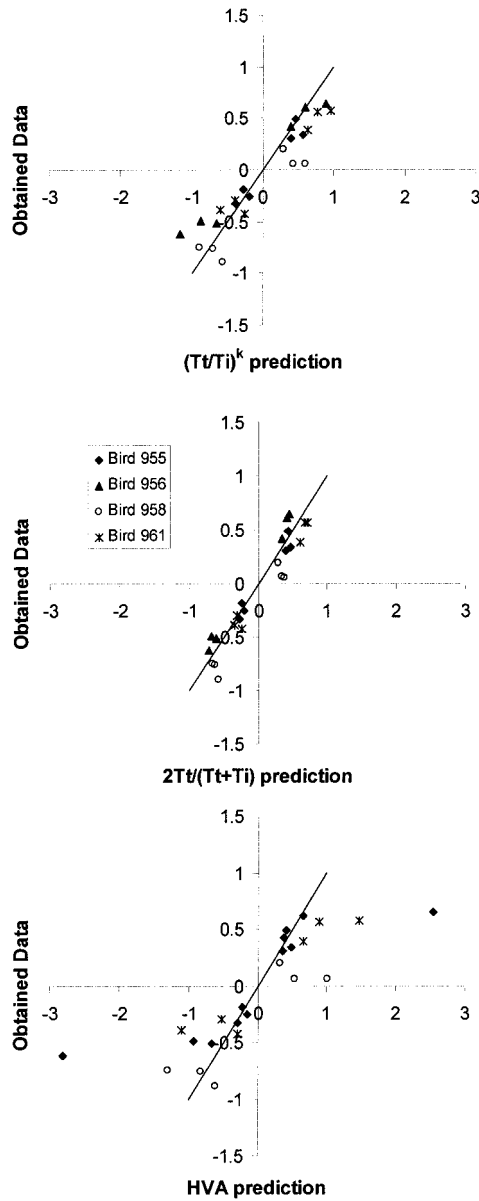


Fig. 8. The log initial-link response ratios from Experiment 2, as a function of the predictions made by CCM with temporal context represented as $(Tt/Ti)^k$ (top panel) and $2Tt/(Tt+Ti)$ (middle panel), and HVA (bottom panel), using parameters estimated from Experiment 1. The diagonal line in each panel represents perfect prediction, and data for individual subjects are marked as noted in the legend.

ing the parameters estimated from Experiment 2. Predictions for some pigeons (e.g., 958 and 956) appear predominantly above or below the major diagonal, indicating shifts in

bias across experiments (cf. Tables 3 and 4). Pooled across subjects, systematic deviations are evident for $(Tt/Ti)^k$ and HVA but not $2Tt/(Tt + Ti)$. Correlations of residuals and predicted values were significant for $(Tt/Ti)^k$ and HVA, $r = -.64$, $p < .001$, and $r = .28$, $p < .01$, respectively. This indicates that $(Tt/Ti)^k$ was systematically predicting response allocation that was more extreme than obtained, whereas HVA was predicting response allocation that was less extreme. The correlation for $2Tt/(Tt + Ti)$ was not significant ($r = -.08$), which confirms that predicted and obtained values did not differ systematically for this model. Thus these analyses suggest that CCM with temporal context represented as $2Tt/(Tt + Ti)$ provides the best account of the data from both experiments.

Additional insight into the models' predictions is provided by Figure 10, which shows obtained preference, averaged across subjects, for the 2:1, $Ti = 15$ condition from Experiment 1 (unfilled symbols) and the 2:1, $Ti = 8$ condition from Experiment 2 (filled symbols). The Tt/Ti ratios for these conditions are 0.5, 1, and 2 for the Experiment 1 data, and 3, 6, and 12 for Experiment 2. Predictions of the models are shown, and were generated by fitting the models to the average data from Experiment 1. Figure 10 shows that all three models made similar predictions for the conditions from Experiment 1, but the predictions diverged as the Tt/Ti ratio was increased in Experiment 2. Whereas the predictions of HVA rise almost linearly, $2Tt/(Tt + Ti)$ predicts that preference should reach an asymptotic level with increases in Tt/Ti . The data supported the latter prediction. This suggests there is an upper bound to the terminal-link effect: As terminal-link duration increases relative to initial-link duration, preference does not increase indefinitely but rather reaches an asymptotic level.

GENERAL DISCUSSION

The purpose of the present experiments was to study how relative initial-link responding in concurrent chains changes as the temporal context of reinforcement is varied, by increasing terminal-link duration relative to initial-link duration with the ratio of terminal link schedules held constant. Temporal context was quantified as the ratio of average ter-

Table 4

Estimated parameter values and variance accounted for (VAC) when three models—CCM with context represented as $(Tt/Ti)^k$, or $2Tt/(Tt+Ti)$, and HVA—were fitted to the data from all subjects in Experiment 2.

Model	Pigeon															
	955				956				958				961			
	<i>b</i>	<i>a</i> ₂	<i>k</i>	VAC	<i>b</i>	<i>a</i> ₂	<i>k</i>	VAC	<i>b</i>	<i>a</i> ₂	<i>k</i>	VAC	<i>b</i>	<i>a</i> ₂	<i>k</i>	VAC
$(Tt/Ti)^k$	1.15	0.84	0.12	0.958	1.02	1.23	0.22	0.994	0.45	1.51	0.00	0.980	1.18	1.16	0.13	0.979
$2Tt/(Tt+Ti)$	1.15	0.62		0.959	1.02	1.09		0.993	0.45	0.88		0.951	1.18	0.86		0.978
HVA	1.15	0.56		0.950	1.02	0.88		0.979	0.45	0.76		0.897	1.18	0.77		0.962

Average VAC: $(Tt/Ti)^k$, 0.978; $2Tt/(Tt+Ti)$, 0.970; HVA, 0.947.

minal-link to initial-link duration (Tt/Ti). Previous studies have established that relative initial-link responding becomes more extreme with increases in Tt relative to Ti , but the precise nature of the functional relation is not clear (MacEwen, 1972; Williams & Fantino, 1978).

Experiment 1 sought to determine whether preference, measured as the log initial-link response ratio, increases as a positively accelerated, linear, or negatively accelerated function of Tt/Ti when terminal-link duration is increased relative to initial-link duration. Models for concurrent chains make different predictions for this situation. Delay-reduction theory (DRT; Fantino et al., 1993) predicts a positively accelerated increase, the simplest form of Grace's (1994) contextual choice model (CCM; with temporal context represented as Tt/Ti) predicts a linear increase, whereas CCM with temporal context represented as either $(Tt/Ti)^k$ ($k < 1$) or $2Tt/(Tt + Ti)$, and Mazur's (2001) hyperbolic value-added (HVA) model predict a negatively accelerated increase (see Figure 1). Overall, point estimates of the slope of the relation between preference and Tt/Ti decreased as Tt/Ti increased from 0.5 to 1.0, and 1.0 to 2.0, for two different absolute durations of Tt and Ti . This is evidence that preference increases as a negatively accelerated function of Tt/Ti when terminal-link duration is increased, and indicates that both DRT and the simplest version of CCM fail to describe this relation adequately.

Another goal of Experiment 1 was to test whether temporal context effects depended on the relative, not absolute, terminal- and initial-link durations. Specifically, preference should not change if Tt and Ti are increased

by the same factor. Support for this ratio invariance, which is required by both CCM and DRT, has previously been reported by Grace and Savastano (2000). They found that preference for a VI 10-s over VI 20-s terminal link, with $Ti = 15$ s, was equal to preference for a VI 20-s over VI 40-s terminal link with $Ti = 30$ s. In the present Experiment 1, preference in the $Ti = 15$ -s conditions was approximately equal to preference in the corresponding $Ti = 30$ -s conditions (see Figure 5). Deviations were relatively small and unsystematic, providing additional evidence that the ratio invariance predicted by CCM and DRT characterizes choice in concurrent chains, at least to a reasonable approximation.

One question that could be raised is whether the results were influenced by using a three-component concurrent chains procedure (effectively a multiple schedule), compared with traditional procedures in which only one set of initial- and terminal-link schedules is presented. Using a similar procedure in which the reinforcer magnitudes differed across components, Grace (1995) found a systematic induction effect: response allocation was slightly biased towards the side correlated with the larger reinforcer from the previous component, although the effect was small and transient. Because component order was randomized within each session, it is unlikely that such induction effects would have affected results in a systematic way. Overall, the data are highly consistent with those from previous studies. The average a_2 values were 0.88 and 0.90 for CCM with temporal context represented as $(Tt/Ti)^k$ and $2Tt/(Tt + Ti)$ fitted to the data from Experiment 1, respectively. These values are nearly identical to the average of 0.90 reported by Grace

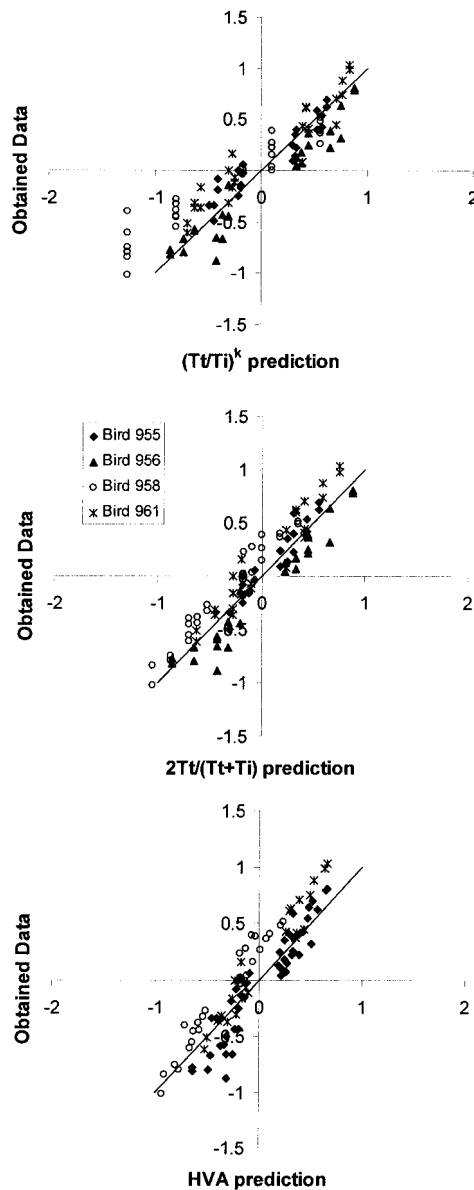


Fig. 9. The log initial-link response ratios from Experiment 1, as a function of the predictions made by CCM with temporal context represented as $(Tt/Ti)^k$ (top panel) and $2Tt/(Tt + Ti)$ (middle panel), and HVA (bottom panel), using parameters estimated from Experiment 2. The diagonal line in each panel represents perfect prediction, and data for individual subjects are marked as noted in the legend.

(1994) in his reanalysis of archival studies using VI terminal links. Thus the results do not appear to have been affected by the multiple component procedure in any systematic way,

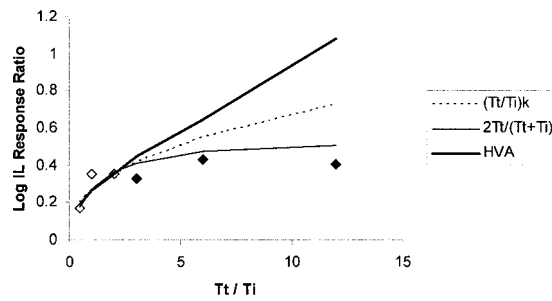


Fig. 10. Log initial-link response ratios for the average data from Experiment 1 (unfilled symbols) and Experiment 2 (filled symbols), together with the predictions of CCM with temporal context represented as $(Tt/Ti)^k$ and $2Tt/(Tt + Ti)$, and HVA. For all conditions the terminal-link ratio was 2:1. See text for more explanation.

although it is difficult to rule out this possibility entirely, of course.

The three models that predicted a negatively accelerated relation between preference and relative terminal-link duration— $(Tt/Ti)^k$, $2Tt/(Tt + Ti)$, and HVA—were fitted to individual subject data in Experiment 1. Overall, each model provided an excellent description of the data, accounting for approximately 93% of the variance in relative initial-link responding. The reason that the models performed about equally well is simple: their predictions were similar to a remarkable degree. For example, the correlation between preference values predicted by $2Tt/(Tt + Ti)$ and HVA were $r = .995$ for Pigeon 955's data, and $r = .999$ for the other 3 pigeons. Averaged across subjects and conditions, the median absolute deviation between the predictions of $2Tt/(Tt + Ti)$ and HVA was 0.021 log units (the average was 0.024). Because this difference is small relative to the degree of variability typically observed in subjects' behavior, the implication is that for all practical purposes CCM and HVA are empirically equivalent for the range of conditions studied in Experiment 1, at least in terms of their ability to describe the data post hoc.

The difficulty with comparisons based on fits to data is that the models contain sufficient flexibility in the form of free parameters to account for nearly all the structure in the data. However, Experiment 2 provided a strong a priori test of the models' predictions. Two conditions were studied in which the range of programmed Tt/Ti values was ex-

Table 5

Percentages of variance accounted for by three different models of concurrent-chains performance: CCM with temporal context represented as $(Tt/Ti)^k$ and $2Tt/(Tt+Ti)$, and HVA. Each model was fit to the studies listed below.

Study	$(Tt/Ti)^k$	$2Tt/(Tt+Ti)$	HVA
Alsop & Davison, 1988	90.6	91.6	90.7
Chung & Herrnstein, 1967	91.0	90.2	90.5
Davison, 1976	98.2	98.1	95.6
Davison, 1983	81.5	76.1	82.6
Davison, 1988	91.6	91.8	88.7
Davison & Temple, 1973	92.0	94.1	90.4
Duncan & Fantino, 1970	98.1	98.8	95.2
Dunn & Fantino, 1982	99.6	95.9	94.6
Fantino, 1969	99.1	96.9	97.2
Fantino & Davison, 1983	92.1	90.2	91.4
Fantino & Royalty, 1987	81.0	80.5	78.3
Gentry & Marr, 1980	78.1	72.3	80.4
Killeen, 1970	98.5	98.8	98.1
MacEwen, 1972	92.0	98.1	93.1
Omino & Ito, 1993	95.4	95.4	93.4
Preston & Fantino, 1991	75.2	80.1	72.5
Squires & Fantino, 1971	85.9	85.9	85.9
Wardlaw & Davison, 1974	93.9	93.6	93.0
Williams & Fantino, 1978	90.9	91.2	90.8
Average	90.8	90.5	89.6

tended to 3, 6, and 12. For each model, predictions were made based on the best-fitting parameter estimates obtained in Experiment 1. The results were clear: predictions of $2Tt/(Tt + Ti)$ were the most accurate, with no systematic deviations, whereas predictions of HVA and, to a lesser extent $(Tt/Ti)^k$, were too extreme (see Figure 8). The data show that with increases in terminal-link duration preference appears to reach an asymptote, rather than continuing to increase to the extent predicted by $(Tt/Ti)^k$ and HVA (see Figure 10).

These results provide evidence that temporal context effects are better represented for CCM as $2Tt/(Tt + Ti)$, compared with the original version of the model that used Tt/Ti or $(Tt/Ti)^k$. As noted in the introduction, these functions are all specific instances of a more general model, in which temporal context effects are a function of Tt/Ti (Equation 2). Grace (1994) noted that the existing studies did not allow for the precise nature of the function to be determined, and thus Tt/Ti was preferred as the simplest possible representation of temporal context. The present experiments that manipulated Tt/Ti directly, however, provide the following characterization of the terminal-link effect: log relative initial-link response rate increases in a nega-

tively accelerated fashion as Tt increases relative to Ti , eventually reaching an asymptotic level. Overall, the pattern is described well as a hyperbolic function of the Tt/Ti ratio.

Representing temporal context as $2Tt/(Tt + Ti)$ may be appropriate for the present data, but how well does it account for the archival studies that Grace (1994) examined? Table 5 shows the results of an analysis in which CCM was fitted to the same 92 data sets that were used initially to develop the model. Each model was fitted to individual data sets, and the percentages of variance accounted for were averaged within studies. Across the 19 studies, $2Tt/(Tt + Ti)$ accounted for 90.5 percentage of the variance, compared with 90.8 for the original version of CCM and 89.6 for HVA. Thus it was able to describe the archival studies about as well as the original version of CCM. It is also important to note that one extra parameter was used for 10 data sets with $(Tt/Ti)^k$ (k) and HVA (K), but $2Tt/(Tt + Ti)$ does not include this parameter. The conclusion, then, is that although the studies analyzed by Grace (1994) were insufficient to determine the functional relation between preference and Tt/Ti precisely (i.e., f in Equation 2), the present studies indicate that terminal-link sensitivity increases as a hyperbolic function of Tt/Ti .

The success of $2Tt/(Tt + Ti)$ underscores an important similarity between concurrent chains and autoshaping that has been noted by previous authors (e.g., Preston & Fantino, 1991). In both procedures, periods of signaled nonreinforcement (i.e., the initial links in concurrent chains, and the intertrial interval $[I]$ in autoshaping) alternate with periods of signaled delayed reinforcement (i.e., terminal links in concurrent chains and conditional stimulus $[CS]$ duration $[T]$ in autoshaping). In both procedures, the overall temporal context of reinforcement, that is, the relative durations of the nonreinforcement and signaled delayed reinforcement periods, has strong effects on behavior. But beyond the qualitative similarity of these context effects, there may be a quantitative one: Gibbon et al. (1977) found that rate of acquisition in autoshaping was constant for constant ratios of the intertrial interval to trial duration, a result that parallels the ratio invariance predicted by CCM and DRT. Primarily to incorporate the effect of reinforcers delivered during the intertrial interval, which retard acquisition, Gibbon and Balsam (1981) proposed that acquisition of keypecking in autoshaping was a function of the ratio C/T , where C is the average interreinforcer interval ("cycle time") and T is the CS duration. Because the average interreinforcer interval in concurrent chains is $Tt + Ti$, and the CS duration is analogous to Tt , this suggests that $2Tt/(Tt + Ti)$ may represent essentially the same ratio comparison as C/T . It seems plausible that there should be a relation between models for autoshaping and preference in concurrent chains because Pavlovian conditioning has traditionally been assumed to be the process whereby terminal-link stimuli acquire differential value.

Overall, the present data are the first to describe the terminal-link effect in quantitative detail. The strength of preference in concurrent chains, measured as the log initial-link response ratio, increases as a hyperbolic function of terminal-link duration relative to initial-link duration. Several different quantitative models can describe these data with a high degree of accuracy, but the results overall, especially Experiment 2, are best accounted for by a modified version of CCM in which temporal context is represented by $2Tt/(Tt + Ti)$.

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APPENDIX

Raw data for all subjects from Experiments 1 and 2. Listed for each condition and component are the VI schedules (in seconds) associated with the left and right terminal links, the average programmed time in the terminal (Tt) and initial (Ti) links (in seconds), the responses made to the left and right initial links (BL and BR), and the number of obtained entries to the left and right terminal links (eL and eR). Data are aggregated over the last 10 sessions of each condition.

Pi-geon	Condition	Component	VI - left	VI - right	Tt	Ti	BL	BR	eL	eR
955	Experiment 1									
	4:1									
	($Ti=15$)	Red	3	12	7.5	15	3114	682	130	110
		Green	6	24	15	15	2733	567	155	85
		White	12	48	30	15	3253	411	148	92
	1:4									
	($Ti=15$)	Red	12	3	7.5	15	1612	2054	117	123
		Green	24	6	15	15	831	2887	114	126
		White	48	12	30	15	1115	2682	114	126
	2:1									
	($Ti=15$)	Red	5	10	7.5	15	2325	1348	119	121
		Green	10	20	15	15	2435	978	126	114
		White	20	40	30	15	2409	940	121	119
	1:2									
	($Ti=15$)	Red	10	5	7.5	15	1833	1618	119	121
		Green	20	10	15	15	1336	2101	115	125
		White	40	20	30	15	1706	1630	122	118

APPENDIX

Continued.

Pi- geon	Condition	Compo- nent	VI - left	VI - right	Tl	Ti	BL	BR	eL	eR
956	4:1 ($Ti=30$)	Red	6	24	15	30	4334	1698	121	119
		Green	12	48	30	30	4612	1227	125	115
		White	24	96	60	30	4588	1040	123	117
	1:4 ($Ti=30$)	Red	24	6	15	30	2174	3169	123	117
		Green	48	12	30	30	1366	3203	116	124
		White	96	24	60	30	1521	3370	119	121
	2:1 ($Ti=30$)	Red	10	20	15	30	3376	2789	119	121
		Green	20	40	30	30	3038	2119	122	118
		White	40	80	60	30	3427	2107	118	122
	1:2 ($Ti=30$)	Red	20	10	15	30	2255	2410	120	120
		Green	40	20	30	30	1653	2199	123	117
		White	80	40	60	30	1481	2621	120	120
	Experiment 2									
	1:2 ($Ti=8$)	Red	32	16	24	8	734	1312	120	120
		Green	64	32	48	8	576	1040	110	130
		White	128	64	96	8	540	1220	116	124
	2:1 ($Ti=8$)	Red	16	32	24	8	1281	570	114	102
		Green	32	64	48	8	1422	415	114	102
		White	64	128	96	8	1173	456	117	99
	Experiment 1									
	4:1 ($Ti=15$)	Red	3	12	7.5	15	3253	1190	127	113
		Green	6	24	15	15	5200	826	142	98
		White	12	48	30	15	4195	474	142	98
	1:4 ($Ti=15$)	Red	12	3	7.5	15	1409	5643	116	124
		Green	24	6	15	15	875	5335	104	136
		White	48	12	30	15	733	5579	111	129
	2:1 ($Ti=15$)	Red	5	10	7.5	15	2554	1733	126	114
	Green	10	20	15	15	3114	2015	122	118	
	White	20	40	30	15	2203	1064	129	111	
1:2 ($Ti=15$)	Red	10	5	7.5	15	1522	1945	124	116	
	Green	20	10	15	15	1641	4319	122	118	
	White	40	20	30	15	546	4741	112	128	
4:1 ($Ti=30$)	Red	6	24	15	30	6508	3556	126	114	
	Green	12	48	30	30	5800	2594	124	116	
	White	24	96	60	30	7220	839	138	102	
1:4 ($Ti=30$)	Red	24	6	15	30	2179	8319	121	119	
	Green	48	12	30	30	1133	8050	113	127	
	White	96	24	60	30	1072	7725	109	131	
2:1 ($Ti=30$)	Red	10	20	15	30	3795	3070	127	113	
	Green	20	40	30	30	3399	2658	125	115	
	White	40	80	60	30	4156	1727	122	118	
1:2 ($Ti=30$)	Red	20	10	15	30	2529	7572	115	125	
	Green	40	20	30	30	1692	7698	121	119	
	White	80	40	60	30	1564	7532	117	123	

APPENDIX

Continued.

Pi- geon	Condition	Compo- nent	VI - left	VI - right	Tt	Ti	BL	BR	eL	eR
958	Experiment 2									
	1:2 ($Ti=8$)	Red	32	16	24	8	862	2998	116	124
		Green	64	32	48	8	677	2807	103	137
		White	128	64	96	8	626	3162	109	131
	2:1 ($Ti=8$)	Red	16	32	24	8	2939	933	130	110
		Grn	32	64	48	8	2923	571	133	107
		Whit	64	128	96	8	2996	514	136	104
	Experiment 1									
	4:1 ($Ti=15$)	Red	3	12	7.5	15	4359	1695	124	116
		Green	6	24	15	15	4270	1834	121	119
		White	12	48	30	15	3836	1302	118	122
	1:4 ($Ti=15$)	Red	12	3	7.5	15	865	3884	114	126
		Green	24	6	15	15	448	4304	95	145
		White	48	12	30	15	404	4268	95	145
	2:1 ($Ti=15$)	Red	5	10	7.5	15	3171	1885	120	120
		Green	10	20	15	15	3192	1522	127	113
		White	20	40	30	15	3285	1302	122	118
	1:2 ($Ti=15$)	Red	10	5	7.5	15	2089	3827	122	118
		Green	20	10	15	15	1356	3741	121	119
		White	40	20	30	15	1232	3895	114	126
	4:1 ($Ti=30$)	Red	6	24	15	30	7303	4013	120	120
		Green	12	48	30	30	6456	2820	114	126
		White	24	96	60	30	7251	2151	122	118
	1:4 ($Ti=30$)	Red	24	6	15	30	2851	8036	113	127
		Green	48	12	30	30	1466	8741	117	123
		White	96	24	60	30	621	9732	96	144
	2:1 ($Ti=30$)	Red	10	20	15	30	6172	6048	122	118
		Green	20	40	30	30	5206	4989	118	122
		White	40	80	60	30	5950	4184	120	120
	1:2 ($Ti=30$)	Red	20	10	15	30	3442	8042	115	125
		Green	40	20	30	30	2787	6887	119	121
		White	80	40	60	30	2174	7747	120	120
961	Experiment 2									
	1:2 ($Ti=8$)	Red	32	16	24	8	112	4005	43	197
		Green	64	32	48	8	199	3194	63	177
		White	128	64	96	8	158	2804	58	182
	2:1 ($Ti=8$)	Red	16	32	24	8	1773	1104	121	119
		Green	32	64	48	8	1384	1197	120	120
		White	64	128	96	8	1356	1049	127	113
	Experiment 1									
	4:1 ($Ti=15$)	Red	3	12	7.5	15	4211	791	123	117
		Green	6	24	15	15	4514	625	136	104
		White	12	48	30	15	5541	324	154	86
	1:4 ($Ti=15$)	Red	12	3	7.5	15	2443	3609	119	121
		Green	24	6	15	15	1950	3891	122	118
		White	48	12	30	15	1440	4980	116	124

APPENDIX

Continued.

Pi- geon	Condition	Compo- nent	VI - left	VI - right	Tt	Ti	BL	BR	eL	eR
	2:1 ($Ti=15$)	Red	5	10	7.5	15	3086	2430	123	117
		Green	10	20	15	15	4813	1177	121	119
		White	20	40	30	15	4175	1564	128	112
	1:2 ($Ti=15$)	Red	10	5	7.5	15	2669	3584	118	122
		Green	20	10	15	15	2379	3553	119	121
		White	40	20	30	15	1878	3915	119	121
	4:1 ($Ti=30$)	Red	6	24	15	30	6279	1959	128	112
		Green	12	48	30	30	8081	835	135	105
		White	24	96	60	30	7899	544	138	102
	1:4 ($Ti=30$)	Red	24	6	15	30	2874	7307	115	125
		Green	48	12	30	30	2835	6832	117	123
		White	96	24	60	30	1940	8386	117	123
	2:1 ($Ti=30$)	Red	10	20	15	30	6189	2191	123	117
		Green	20	40	30	30	6429	1397	125	115
		White	40	80	60	30	6491	2365	124	116
	1:2 ($Ti=30$)	Red	20	10	15	30	3939	4686	119	121
		Green	40	20	30	30	4479	2993	122	118
		White	80	40	60	30	3669	3694	120	120
Experiment 2										
	1:2 ($Ti=8$)	Red	32	16	24	8	1146	3240	116	124
		Green	64	32	48	8	1256	2950	109	131
		White	128	64	96	8	1031	3318	104	136
	2:1 ($Ti=8$)	Red	16	32	24	8	2424	910	125	115
		Green	32	64	48	8	3357	653	140	100
		White	64	128	96	8	2950	537	143	97